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## Review Article

# A review: drilling performance and hole quality of aluminium alloys for aerospace applications



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## ABSTRACT

Despite the growth of composites and other lightweight materials, aluminium alloys remain an attractive choice of the aerospace industry due to their mature manufacturing processes, good resistance to fatigue crack growth and superior damage tolerance. In the aerospace industry, the drilling process is the most challenging among all the other machining process as millions of holes are required for producing riveted and bolted joints in the assembly operation of the aircraft's structures. The major challenges which arise from the drilling of these alloys are characterized by the poor hole quality which might initiate cracks within the airframe structure and reduces their reliability. This results in the rejection of parts at the assembly stage which directly impacts the manufacturing cost. Hence, appropriate selection of tool geometry, tool material and coatings, optimal cutting speed and feed rate, as well as drilling machines, is required to meet the requirement of machined parts. This motivates both academia and industries to further research on the application of drilling operations in the aircraft industry. This review aims to document details on drilling forces, drilling parameters, drill tool geometry, drill materials and coatings, chips formation, analysis of tool wear and hole metrics such as the hole size and circularity error, surface roughness, and burrs formation during the drilling of different aluminium alloys used in the aerospace industry. The focus will be mainly on Al2024 and Al7075 alloys since they are most commonly used and reported in the open literature.

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## 1. Introduction

Aluminium is a consumer metal of great importance due to its high range of applications in industries like automotive, building and construction, electrical and electronics, transport, marine as well as aerospace industries [1]. The future market forecasts predict that the aluminium market will rise to US\$189.8 billion by 2026 rising from US\$147.2 billion in 2018

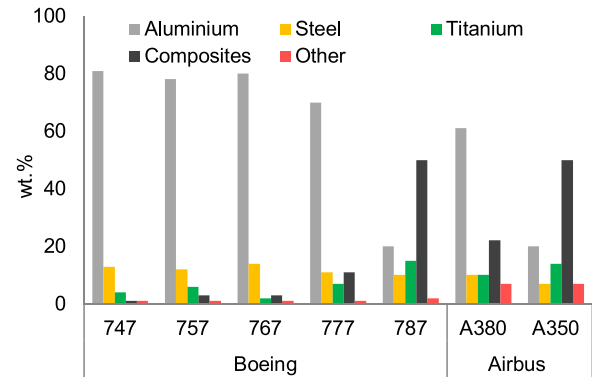


Fig. 1 – Aluminium in commercial airlines [4].

[1]. In the automotive industry alone, it has been projected that the average content of aluminium in a car will reach 250 kg by 2025, compared to 35 kg in the 1970s [2] and it accounts for 40% of the weight of certain private cars [3]. In addition, 80% of the weight of a typical civilian aircraft is composed of aluminium. Fig. 1 shows the use of aluminium in commercial airlines [4].

The application of aluminium alloys and numerical designation with a main alloying element as well as modifications of alloy with the class according to the aluminium association is given Table 1 [5,6].

In the aerospace industry, the introduction of composites has limited the role of aluminium in airframe designs up to a certain extent due to aspects of their fatigue performance, reduced weight, and corrosion resistance. However, low impact resistance, complex mechanical behaviour due to environmental conditions i.e. moisture absorption as well as repair and recycling remains a considerable challenge for composite [4]. Correspondingly, aluminium alloys are still used in the aerospace industry as a structural material due to their mature manufacturing processes, corrosion resistance, lightweight, and low cost relative to other metals and composites [7].

The important parameters for designing aircraft structure include fatigue resistance, density, fracture toughness, strength, and corrosion resistance [7]. Additionally, there is a compressive load on the upper side when subjected to tension during static weight, where the opposite happens to the lower part; therefore, careful optimization of tensile and compressive strength is needed during flight [7]. Thus, aluminium being the lightest metal can readily replace other metals and sustain pressure loading on the wings which has increased due to the construction of larger aircraft [8]. In this regard, different types of aluminium alloys are used in the aerospace industry where some of them are given in Table 2. However, the common classes are mostly from 2xxx and 7xxx series [9]. 2000 series alloys have good resistance to fatigue crack growth and possess superior damage tolerance. Therefore, they are commonly used in fuselage skins and in the lower wings of aircraft where fracture toughness i.e. resistance to crack growth is an important design parameter [6]. Al2024-T3 is the most common 2000 series alloy used in fuselage construction [10]. The 7000 series are normally used in the upper wing skins, where strength is the primary design factor [6]. Al7075-T6 is

**Table 1 – Description of aluminium alloys [5,6].**

Series	Main alloying elements	Applications
1XXX	Commercially pure aluminium >99% purity	Low cost commercially pure having no alloying elements. Mainly used in chemical industries due to its resistance to chemical attack and corrosion. Also, used in electrical appliances due to superior conductivity
2XXX	Copper	Used in an aircraft application, susceptible to corrosion as compared to other alloys. Alloys such as Al2024 have superior machinability
3XXX	Manganese	Used in anodizing and welding applications
4XXX	Silicon	Used for welding wires and brazing alloy for joining aluminium, mostly used for architectural applications
5XXX	Magnesium	Good welding characteristics and resistance to corrosion in seawater applications
6XXX	Magnesium and Silicon	With an equal amount of magnesium and silicon, alloys in this series are used in automotive applications, they have good formability, machinability and corrosion resistance
7XXX	Zinc	Highest strength among all series. Mainly used in aircraft structures and mobile applications
8XXX	Other elements (including lithium)	Reserved for alloying elements other than those used for Al2xxx to 7xxx such as iron, nickel, aluminium-lithium alloy.
<p><i>Designation system</i>  1st digit shows the alloy types, 2nd digit shows the alloy modifications if other than 0 whereas 3rd and 4th digits represent the purity of aluminium of the specific aluminium alloy</p> <p><i>Temper designation for aluminium alloy</i>  Suffix letter “F,” “H,” “O,” “T,” or “W” indicates basic treatment condition  F: As-fabricated  O: Annealed (wrought products only)  W: Solution-treated  H: Cold-worked (strain hardened)  T: Age-hardened  T1: Cooled from fabrication temperature and naturally aged  T2: Cooled from fabrication temperature, cold-worked and naturally aged  T3: Solution treated, cold-worked and naturally aged  T4: Solution treated and naturally aged  T5: Cooled from fabrication temperature and artificially aged  T6: Solution-treated and artificially aged  T7: Solution-treated and stabilised by over-ageing  T8: Solution-treated, cold-worked and artificially aged  T9: Solution-treated, artificially aged and cold-worked  T10: Cooled from fabrication temperature, cold-worked and artificially aged</p>		

**Table 2 – Alloys of aluminium used in the aviation industry [7,12–14].**

Aluminium alloy	Typical application in the aviation industry
Al2024-T3 Al2024-T4, 2524, 2224-T351, and 2324-T39	Fuselage skin, wing skins, cowls, also used for repair and restoration
6061-T6 Al3003	Landing mats, frames, fuselage and wings Cowls and baffle plating.
Al5052-H32 Al3003-H14	Fuel tanks Cowls and baffle plating
Al7075 Al2219	Wing skin and fuselage (military aircraft) The external fuel tank on the first successfully launched space shuttle, Columbia.
Al6063	Aesthetic and architectural finishes and intricate extrusions
Al7475, Al7075-T6	Fuselage bulkheads of larger aircraft, wing skins, stringers and horizontal/vertical stabilizers

the best-known alloy of the 7000 series that is used in aircraft applications [11].

## 2. Performance evaluation of drilling in the aerospace industry

In the aerospace industry, drilling with a twist drill is the most important machining process as millions of holes are required for the assembly operations of an aircraft structure, especially in producing riveted and bolted joints [15]. These structures usually undergo constant shock and vibration during aircraft service which could promote fatigue failure due to cyclic loading below the material yield strength [16]. Also, the fastener holes are produced manually using pneumatic hand-held drilling units in which the drill feeds into the fuselage skin of the aircraft [16]. In the drilling process, the material is removed by the chisel edge where the chips are evacuated through the flutes. This causes the generation of high thrust force and the effective dissipation of heat becomes difficult [17]. The generated heat, which is caused by the friction between the drill, chip, and fuselage skin, increases the surface roughness and consequently develops the regions of stress concentration [18]. When fastener holes in the fuselage skin of aircraft create regions of concentrated stress, there are chances of propagation of fatigue cracks which directly affect the fatigue life of aircraft structures and reduce their reliability [19]. The fatigue life of metal aircraft structures depends on the material properties which are highly influenced by the machining process parameters and cutting tool used for hole making process [20]. Furthermore, the plastic deformation of workpiece by the tool causes residual stresses which are strongly affected by the machining parameters [21]. Therefore, the residual stress in the hole surface can also contribute to the fatigue behaviour of the alloys [16]. Previous studies reported that the residual stresses in a hole vary with its thickness and are higher at the exit side than at the entrance of the hole [22]. In addition, there is a possibility of micro-smearing. Smearing is undesirable in the aerospace industry as it covers the surface defects and cracks, thus leading to premature failure of components [23]. Hence, the life of the joint depends

on the quality of holes which is based on drilling performance [24].

Therefore, the major challenge of drilling in aeronautical structures is the stringent requirements of hole quality metrics by the aerospace industry [25]. Some of the most important hole metrics are hole surface finish, which is also known as the hole surface roughness, burr formation, and dimensional accuracy including deviation from hole size, and circularity error [26]. Thus, maintaining a good hole quality is important to avoid crack initiation within the airframe structure, which is one of the main reasons for part rejection at the assembly stage [16]. To overcome these problems, jigs are used in the aircraft industry to provide an effective drilling approach. The drilling jigs help to position the handheld drilling unit into the right drilling point on the structure, keep the connecting holes normal to the mating interfaces, and prevent deviation caused due to tool vibration, which allows the mating parts to fit precisely [27]. The process is performed either manually or semi-automatically using drilling machines or drill feed units. However, due to the rising need for aircraft, manufacturers such as Airbus are increasingly moving towards automated processes to generate holes in large numbers with precise tolerances [28]. In addition, Tolouei-Rad [29] describes the utilization of special purpose machines and multi-drill heads when many holes are drilled simultaneously on the same plane. This results in a significant reduction in drilling time while achieving uniformity of holes produced. This can also lead to reduce the use of drilling jigs due to the specific design of spindles and machines.

Furthermore, in aeronautical structures dry drilling is used to reduce the need for cleaning before installing rivets to get high-quality holes [30]. Dry machining is also economical as it eliminates the cost of cutting fluid and the costs associated with its disposal which often exceeds the cost of purchase [31]. In addition, dry machining consumes less electrical power than what is required for the wet machining [32]. Moreover, the use of coolants should have been a focus of intense regulatory scrutiny [33]. In dry machining, chips produced can be recycled and used for other processes without any post-processing whereas the use of the cutting fluid can mix the formed chip and; therefore, needs to go through a proper cleaning process to remove the chemical additives for reuse [34]. Further, dry machining is environmentally friendly and does not impose any hazards to health [35]. Dry machining is also economical and can greatly reduce costs when compared to normally incurred cutting fluids, which has a direct impact on manufacturing costs [36]. Contrastingly, with dry machining, there is a greater chance of tool wear and built-up edge (BUE) which reduces the tool life [37]. This, in turn, requires frequent tool changes which affect the machining process and adds extra costs. Hence, the aerospace industry not only requires materials with specific physical and mechanical properties but also an appropriate selection of tool geometry, tool material and coatings, as well as proper cutting speed and feed, and drilling machines [38]. This motivates both academic and industries to further research the application of drilling operations in the aircraft industry [39]. In addition, most published reviews to date on aluminium alloys have focused on other machining processes with a lack of considerable study on the drilling



of aluminium alloys, especially those used in the aerospace industry. Therefore, the current paper aims to fill this gap and cover different aspects of the drilling process of aluminium alloys with special attention given to aerospace alloys.

### 2.1. Cutting forces in the drilling process

In machining, cutting forces are the result of the cutting tool when it machines the material and gives an idea of how difficult is to machine a certain material [40]. These cutting forces include the primary and secondary cutting forces. The primary cutting forces are the direct force that comes from the relative motion of the tool with respect to the workpiece while the secondary cutting forces are generated as a response to the primary cutting forces such as the occurrence of vibration during machining [40]. Generally, in metal cutting, the material deforms and separated through plastic deformation by the action of the tool. As the tool moves into the material and exceeds its yield strength, there is elastic and then plastic deformation of the material where large forces are produced [41]. However, the cutting forces in metals are uniform because the uncut chip thickness is always constant [40].

In the drilling process, two types of cutting forces are of importance: the axial (often referred to as the thrust) force and the torque. Thrust force ( $F_z$ ) is the perpendicular force to the workpiece surface which is required to keep the cutting tool in the workpiece during its translational motion. The torque is simply known as ( $M_z$ ) is the amount of force required by the machine spindle to rotate the cutting tool during the drilling. Other forces generated in x and y directions are not significant in drilling because they tend to be very small in comparison with the  $F_z$  and  $M_z$  [42]. Cutting forces are the important characteristics of the drilling process as they can directly affect the quality of holes and the cutting tool life, surface quality, vibration, and ultimately power consumption [43].

Fig. 2 shows the forces exerted on a cutting lip and the torque direction. The horizontal force ( $F_H$ ) lies on the XY plane is perpendicular to the axis of the drill bit and generates a resistant torque because it acts itself out at a certain distance from this axis. The normal force ( $F_N$ ) is then divided into two components i.e. the radial force and the thrust force. The radial force ( $F_{rad}$ ) is perpendicular to and the thrust force ( $F_{thrust}$ ) is parallel to the Z-axis [44].

In general, smaller cutting forces are required as high cutting forces might cause the axis of the spindle to rotate more which ultimately affects the quality of any machined surface. High thrust force can also reduce the tool life and sometimes lead to early tool failure while large torque shows that there is more friction between the tool and the workpiece, which means more heat is produced that causes high temperature at the interface of tool-workpiece [45]. Normally, a low thrust force and low torque are possible at a high cutting speed and low feed rate [46]. A high feed rate results in an increase in the chip cross-sectional area where thicker chips are cut thus raise the chipping resistance and the energy required for cutting which consequently increases the thrust force [47–49]. While the high cutting speed might result in high temperature which increases the ductility of the material hence, the thrust force decreases. Therefore, mechanical properties of a material, such as its ductility, hardness or its ultimate ten-

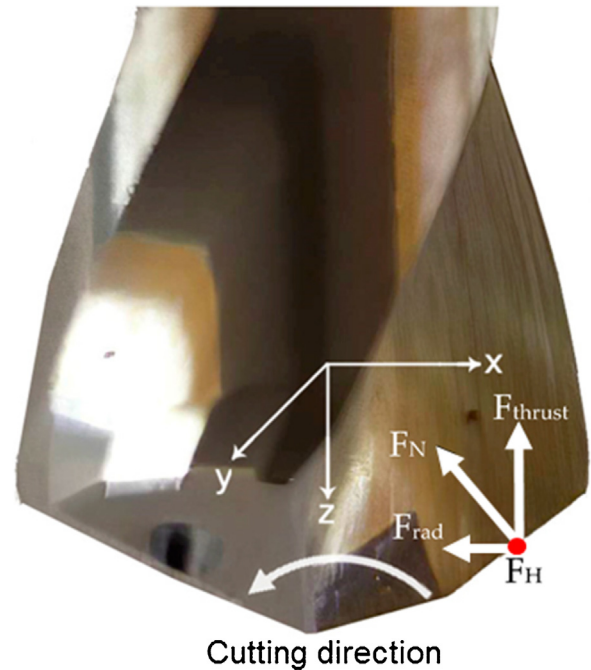


Fig. 2 – The forces exerted on the drill bit [44].

sile strength, might also affect thrust force [50]. Moreover, the drill with large diameter also produces large thrust force and torque due to the greater undeformed chip area. In addition, if the helix angle is greater, there are more chances for the chips to easily form subsequently, there is a decrease in thrust force and torque. Besides, the high point angle also contributes to large thrust force due to the decrease in the undeformed chip thickness provided that all other machining conditions are kept unchanged. Also, Arshinov and Alekseev [51] reported that the larger the chisel edge angle, the larger is the drilling thrust force and torque whereas thinner web reduces the thrust force by (30–35)% compared to a drill having unthinned web. Other parameters affecting the cutting forces include the increase in the number of holes and the tool wear [50]. The factors that affect the drilling cutting forces are given in Fig. 3 [51].

The cutting forces can be measured using a force dynamometer. The typical profiles of thrust force and torque obtained during dry drilling of Al2024 using two-flute twist drill are shown in Fig. 4. The profile is divided into three stages: Drill engagement stage, material removal stage and drill exit stage. Initially, the cutting tool chisel edge penetrated into the workpiece and the cutting lips started to engage in the cutting process. However, the chisel edge of the cutting tool is not fully in contact with the workpiece at this stage. The cutting forces continued to rise till the full engagement of the tool into the workpiece and reached to their peak values where they remain constant throughout the thickness of the workpiece. These cutting forces dropped when the tool reached the end of the workpiece at the exit stage where they followed a profile similar to the entry-stage thus, indicated the completion of the drilling process [53].

It is worth noting that the cutting forces in metals are uniform depends on drilling conditions because the uncut chip

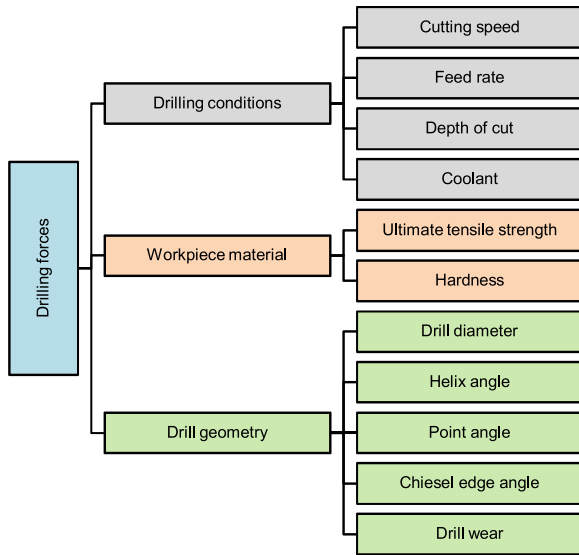


Fig. 3 – Factors affecting drilling forces [52].

thickness is always constant while in composites the cutting forces are cyclic due to the instantaneous changes in the fibre orientation angle [40].

## 2.2. Tool geometry, material and coating

Drilling has a significant share in any industry where tool geometry, as well as tool materials and coatings, play a vital role in producing high-quality holes [15]. For instance, the point angle normally varies between  $80^\circ$  and  $140^\circ$  [54]; however, a smaller point angle is required for metals that have low ductility and a larger one is suggested for materials with a higher toughness [55]. The point angle can also affect the formation of chips and cutting forces which ultimately affect the surface roughness. According to Stephenson and Agapiou [56], thinner chips are produced when the point angle is larger, whereas the size of the chips increases when lowering the point angle. Moreover, the selection of point angle in machining aluminium alloys also depends on the contents of silicon (Si). Alloys of aluminium with high Si content perform better in machining with a point angle in the range of  $115^\circ$ – $120^\circ$ ; con-

trastingly, those with low or no Si contents are recommended with a point angle between  $130^\circ$  and  $140^\circ$  [55]. Furthermore, the helix angle which is considered as the rake angle in other cutting tools is also an important aspect of drill geometry [54]. Generally, a helix angle in the range of  $12^\circ$ – $38^\circ$  is applied in drills depending on the application; however, the standard one is acknowledged as  $30^\circ$  [57]. In addition, a large point angle and a large helix angle favours in reducing burr formation, improving the removal of chips and preventing the materials from sticking to the drill which causes the BUE [58]. Lip clearance angles also fulfil some role in drilling aluminium and are normally found in a range of  $12^\circ$ – $13^\circ$ , where the latter should be increased further to avoid the drill from breakage or when the feed rate is high or the material is soft [59]. Besides, the drill size affects the surface roughness due to rough cuts after the increase in cutting forces and un-deformed chip thickness [60]. However, the common range of tool size in aerospace alloys for creating rivets and holes is usually between 5 and 10 mm [53]. Fig. 5 shows varieties of tool geometries available for drilling process [61–63]; however, twist drills are commonly used which represent an industrial standard and give better hole quality [64].

Another important aspect for drilling of aluminium alloys is the tool material. The tool life depends on the toughness, hardness, wear and thermal resistance of the tool material [40]. HSS tools are considered as the primary choice due to their wide range of availability, low cost and toughness; however, HSS drills are not suitable to perform at high temperature due to compromises in their hardness. Moreover, HSS has a moderate strength which makes them unsuitable to machining [65]. Another important tool material lies in the cemented carbide group is the tungsten carbide. Carbide tool is suitable for better machining due to its high hardness and toughness [40]. In addition to tool materials, the use of coatings, which describe a thin layer of microns applied to a tool surface, can further improve tool performance by increasing the wear resistance. Furthermore, the use of coated tools performs better at high temperature, which makes them a good choice at higher cutting speeds [40]. The coatings to the tools are normally applied using the chemical vapour deposition (CVD) and the physical vapour deposition (PVD) techniques where the typical thickness of coating varies from 2 to 10 mm [66]. Table 3 shows the properties of some coating materials.

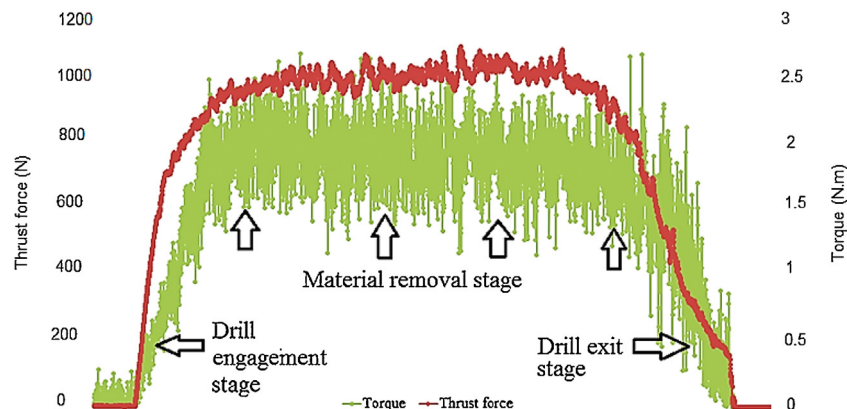


Fig. 4 – Profiles of Thrust force and torque.

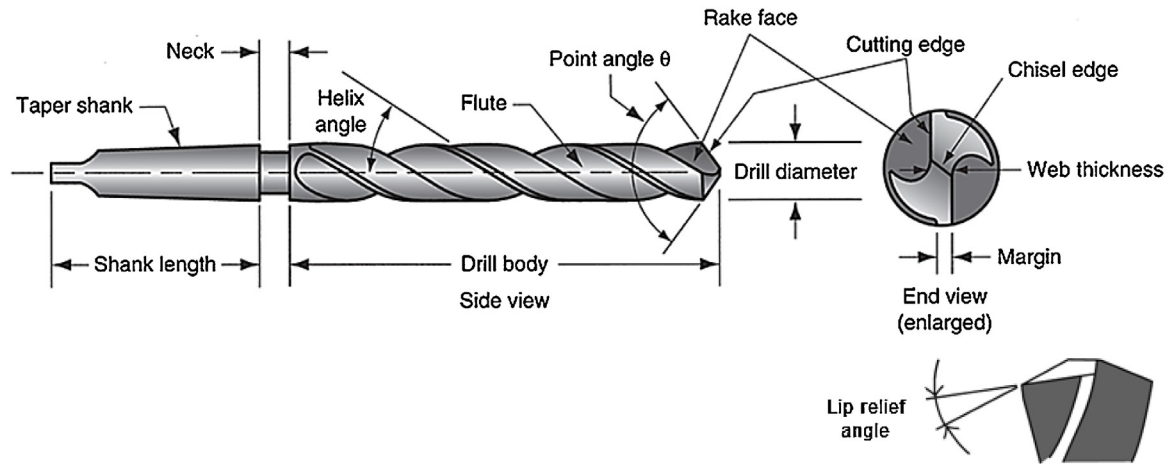


Fig. 5 – Geometry of Twist drill [62,63].

Table 3 – Properties of some cutting tools coating materials [40,67,68].

Material	Oxidation temp (°C)	Hardness (GPa)	Thermal stability (°C)	Friction coefficient
TiN	600	23	500	0.4–0.5
TiCN	400	27	450	0.2
TiAlN	700-800	32	600	0.5–0.7
Al <sub>2</sub> O <sub>3</sub>	>1200	–	–	0.3
CrN	–	21	700	0.6
TiSiN	1000	35	1100	0.6
Diamond	600	90	–	0.05–0.07

The research on different tool geometry, as well as tool material and coatings, is given in Table 4.

For instance, Nouari et al. [58] carried out experiments on Al2024 using uncoated carbide and coated carbide drills with different drill geometries. They concluded that low values of the surface roughness were obtained at high point angle and helix angle. The drill with the highest point angle of 180° also contributed well in minimizing the formation of burrs. In addition, minimum deviation from nominal drill size was obtained when there was a decrease in the web thickness and, increase in helix angle and point angle. Furthermore, it was reported that uncoated drills provided lower surface roughness compared to coated drills, where a possible explanation for this might be due to the low feed rate. However, diamond-coated drills were shown to be better at producing a minimum diameter deviation at high cutting velocity. Overall, their study concluded that coated drills did not contribute well to machining quality except for diamond and (TiAlN + WC/C) coated drills which were found to have results close to those of uncoated drills. In another study by Nouari et al. [69], authors concluded that uncoated and coated carbide drills performed better than HSS drills, giving less deviation from the hole size and low values of surface roughness. Coated carbide drills were further recommended for the best results at high cutting speeds if tool cost is not essential even for fewer holes. This was attributed to the fact that the coating material acted as a thermal barrier from high temperature and limited the diffusion process; thus, reducing tool wear at high cutting speeds. Furthermore, HSS drills were not recommended for dry drilling of Al2024; however, the authors did

not mention any reason for not using the HSS drills, where it is expected that the moderate strength of HSS drill might have made them unsuitable to machining [65]. Rivero et al. [36] used uncoated and coated carbide drills for dry drilling of Al7075-T6. It was found in their study that using Balinit Hardlube low torque, low power consumption, and less burr formation were obtained with increased tool life, specifically at high cutting speeds. On the other hand, more power was consumed using Triton coated tools than when drilling with uncoated drills. Further, it was noted that high power consumption augmented heat which increased plastic deformation of the workpiece, where subsequently the risk for burr formation increased. It was also observed that at the same drilling conditions, the lowest burrs were found when a Hardlube drill was used followed by uncoated drills. The Triton produced the largest burrs, where the authors suggested that Triton coated drills might perform better compared to others when drilling conditions were harder. The study also measured the temperature of the tools using infrared technology. The temperature measured during drilling in coated tools was found to be higher than those in uncoated tools, regardless of drilling parameters. This finding was contrary to results obtained in terms of torque, power consumption and burr formation. The reason for this contradiction was justified by the emissivity of the coatings. The authors expected that adhesion of the workpiece and the wear on coating drills might have changed the emissivity of the tool; thus, rendering the method more sensitive to error. Kurt et al. [70], also studies the impact of cutting speed, point angle, and coating materials on different characteristics of hole quality. The combination of point angle

**Table 4 – Previous studies based on different drilling parameters, drill geometry, materials and coatings.**

Aluminium alloy	Drill geometry	Drilling parameters	Drill material/coatings	Objective	Ref
Al2024-T351	D = 6 $\theta = 130^\circ, 140^\circ, 180^\circ$ $\psi = 30^\circ, 40^\circ$	$V_c = 24\text{--}164$ $f = 0.04$	Uncoated carbide TiAlN coated carbide TiN coated carbide Hardlube: TiAlN + WC/C Diamond coated carbide TiN + Ag coated carbide	R, Z, B,	[58]
Al2024	D = 6 $\theta = 130^\circ$ $\psi = 30^\circ$	$V_c = 25\text{--}165$ $f = 0.04$	Uncoated carbide Uncoated HSS Carbide hardlube: TiAlN + WC/C	R, Z	[69]
Al7075-T6	D = 10 $\theta = 130^\circ$ $\psi = 30^\circ$	$V_c = 150, 200$ and 250 $f = 0.2, 0.3, 0.4, 0.5$ , and 0.6	Uncoated carbide Hardlube: TiAlN + WC/C Balinit Triton: diamond-like carbon	W, B, T, C, P	[36]
Al2024	D = 10 $\theta = 118^\circ$ $\psi = 24, 30^\circ$	$V_c = 30, 45$ and 60 $f = 0.15, 0.20$ and 0.25	Uncoated HSS TiAlN-coated HSS %5 Cobalt-coated HSS TiN-coated HSS	R, Z, C	[70]
Al2024	D = 10.08 $\theta = 118^\circ$ $\psi = 30^\circ$	$V_c = 30, 45$ and 60 $f = 0.15, 0.20$ and 0.25	Uncoated HSS TiAlN HSS TiN HSS	R, Z	[71]
Al7075	D = 5 $\theta = 90^\circ, 118^\circ$ , and 135°	$V_c = 4, 12$ , and 20 $f = 0.1, 0.2$ , and 0.3	HSS drills	B, R	[72]
Al2024, Al7075, Al7050	D = 8, 10, 12	$V_c = 20, 30$ and 40 $f = 0.05, 0.1$ , and 0.15	HSS	B, R	[73]
Al2024	D = 6 $\theta = 130^\circ$ $\psi = 30^\circ, 40^\circ$	$n = 1500$ , and 5000 $f = 0.04$	HSS HSS cobalt	W, Z	[74]
Al-6061, Al-6351, Al-7075	D = 10 $\theta = 90^\circ, 118^\circ$	$n = 90, 200, 250$ , and 400 $f = 0.15, 0.2, 0.3$ , and 0.36	HSS	F, Z	[75]
Al7075	D = 5 $\theta = 120^\circ, 130^\circ$ , and 140	$V_c = 40, 80$ and 120 $f = 0.05, 0.1$ , and 0.15	Tungsten carbide	F	[76]
Al7075	$\theta = 120^\circ, 130^\circ$ , and 140	$V_c = 60, 100$ , and 140 $f = 0.05, 0.1$ , and 0.15	Tungsten carbide	R	[77]
Al 2024	D = 10 $\theta = 118^\circ, 126^\circ$ , and 134°	$V_c = 8, 16$ , and 24 $f = 0.04, 0.08$ , and 0.12	HSS	B	[78]
7076-T6	D = 4.826 $\theta = 110^\circ$ and 130° $\psi = 15^\circ$ and 30°	$n = 1500$ and 2600 $f = 0.05$ and 0.1	Tungsten carbide	R, B, Z, CF	[52]

Symbols: Drill diameter: D (mm), Point angle:  $\phi$ , Helix angle:  $\psi$ , Spindle speed: n (rev/m), Feed: f (mm/rev) Cutting speed:  $V_c$  (m/min), Feed speed:  $V_f$  (mm/min), Cutting forces: F (N), Surface roughness: R ( $\mu\text{m}$ ), Burr formation: B, Circularity/roundness error: C, Hole size: Z, Built-up edge: BUE, Chip formation: CF, Drilling temperature: T, Power: P, Microhardness: H, Tool wear: W.

and selection of coated tool was: 118°, TiN: 118°, TiAlN: 118°, Cobalt (Co) 5%:130°, TiN: 130°. The findings of their study suggested that the high cutting speed and feed rate contributed to the higher values of surface roughness and roundness of holes due to increases in drilling temperatures, vibrations and chatter. The point angle affected only hole size and did not contribute significantly to affect the surface roughness or hole roundness. The uncoated HSS with a point angle of 118° was considered better at low cutting parameters; however, the TiAlN and TiN coated HSS drills with a point angle of 118° were not suggested for drilling at low cutting parameters. Overall, the HSS-Co 5% with a point angle of 130° was found to outperform in all cutting parameters. However, no reason was presented for the best performance of Co 5% HSS drills. Kurt

et al. [71], also confirmed that uncoated HSS drills with low cutting speed and feed rate resulted in low surface roughness and minimum diametral error. Additionally, Kilickap [72] concluded that low burr height and low surface roughness were obtained at low cutting speed low feed rate and highest point angle. Burr height was more affected by point angle followed by feed rate and cutting speed, whereas surface roughness was greatly influenced by cutting speed followed by point angle, and less affected by feed rate. Moreover, Köklü [73] have concluded that feed had more impact on burr height, following the cutting speed and drill size. In addition, higher values of surface roughness were found at high cutting speed as compared with feed rate and drill size. The drill size showed a lower impact on the surface roughness and burr height; however, the



best result in terms of drill size was examined at the lowest drill diameter. Davoudinejad et al. [74] observed in their study that hole size was more affected at the entry side. In addition, the deviation in hole size from its nominal diameter was greater at high cutting speeds, which they related to the high vibration of the tool. The longest tool life was examined at low cutting speed using the HSS-Co drill as compared to HSS drill. The higher cutting speeds were found to be the main reason for the tool wear, which then affected hole quality. In a study by Reddy et al. [75], the diametral error was affected more by the feed rate after the cutting speed and point angle whereas, in case of thrust force, the cutting speed was found to be more dominant, regardless of different alloys. In addition, diametral error and thrust force were high in alloys with a high ductile nature due to high BUE on tools. Gunay et al. [76] reported that low feed rate and high point angle generated low thrust force during drilling of Al7075. However, the highest contribution to thrust force was due to feed rate with minimal impact of point angle and cutting speed. Besides, Yaşar et al. [77] investigated that the surface roughness increased with the increase in cutting speed and feed rate; however, the cutting speed was found to be the major influencing factor as compared to feed rate and point angle. The reason for high surface roughness at high feed rate was justified by the high thrust force which increased the chip volume thus, affected the surface roughness. In addition, a point angle of  $130^\circ$  was recommended for optimal surface roughness. In addition, Kumar et al. [78] concluded that point angle was a significant factor that affected the burr size following the cutting speed, whereas the impact of feed rate on burr size was least significant. Hassan et al. [52] also recommended increasing a point angle from  $110^\circ$  to  $130^\circ$  for the low surface roughness and less formation of burrs around the hole edges.

The above discussion indicates that most of the researchers have recommended a large point angle and a large helix angle for better drill hole quality, improving the removal of chips and preventing the materials from sticking to the drill which causes the BUE. The high drill size affects the surface roughness due to rough cuts after the increase in cutting forces and un-deformed chip thickness. Furthermore, carbide drills are recommended as better tool material due to their high hardness and toughness as compared to HSS. Also, the use of coatings can further improve tool performance by increasing the wear resistance at higher cutting speeds. However, the use of coated tools in drilling aluminium needs further research to overcome the problems associated with the built-up edge and quality of holes.

### 2.3. Characteristics of hole quality

The characteristics of hole quality include the hole size, circularity or roundness error, burr formation, and surface roughness, as given in Fig. 6. High rejection rates of aircraft components reaching 60% are due to poor hole quality in final assembly, which is a challenging problem that requires on-going studies to overcome hole quality issues. Therefore, it is necessary to control the number of rejected parts due to poor hole quality [79]. The following section includes the problems associated with the hole quality



Fig. 6 – Characteristics of hole quality.

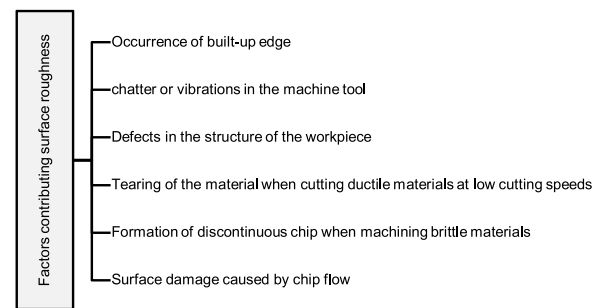


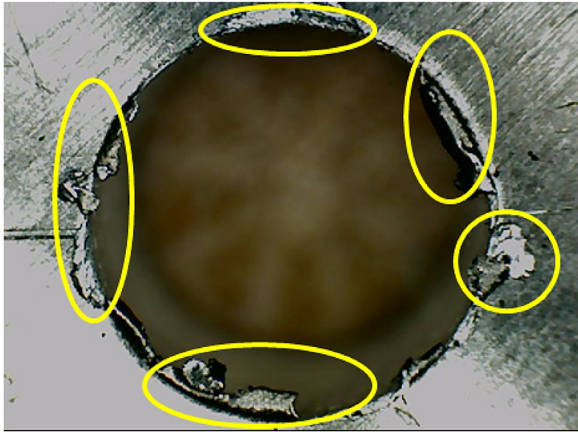
Fig. 7 – Factors that affect surface roughness [81].

and suggestions for their improvement in the drilling process.

#### 2.3.1. Surface roughness, burrs, hole size and circularity error

Surface roughness can measure the surface finish to evaluate surface irregularities of a workpiece due to any machining operations [80]. Surface roughness is generally measured as the average roughness ( $R_a$ ), which is commonly used in the industries [66]. Surface roughness is one of the major characteristics of hole quality, where high surface roughness in holes causes excessive wear and fatigue in the material which has a direct impact on the manufacturing process and ultimately the manufacturing cost. The factors that affect the surface roughness in the drilling process are given in Fig. 7 [81].

Furthermore, during drilling, there are chances of burrs formation. These burrs are small pieces of deformed material and are normally formed at both the entry and exit of holes around hole edges, which affect dimensional accuracy. The burrs at the entrance are usually small and easy to remove when chamfering the holes; however, exit holes are difficult to remove [82]. According to Ko and Lee [83], the material gets plastically deformed as the drill approaches the exit of the



**Fig. 8 – Burrs around the hole edge [91].**

hole, and if the material does not sustain the deformation then it is highly expected that a crack initiated at the edges of the hole. In addition, there is a possibility of fracture either at the centre or in the remaining portion of the hole. Furthermore, when the drill reaches the exit side of a hole, some of the material is pushed out by the thrust force without being cut; thus, forming burrs [84]. According to Mann and Milligan [85], brittle materials are more prone to fracture at this stage as they cannot bear even a small amount of plastic deformation which means that burrs highly depend on material properties. Burrs are also responsible for causing stress concentration which results in fatigue failures, and corrosion; hence, reduces the life of the aircraft. Therefore, de-burring is required to remove burrs which takes up to 30% of the total manufacturing cost [86]. De-burring is generally done manually [87], where the machining time increases and production efficiency reduces [88]. Burr size can be evaluated through height and root thickness. Burrs can be measured using profile-meters [89], optical microscopes [90], and image processing software. Fig. 8 shows the burrs formed during drilling operations [91].

Fig. 9 shows the mechanism of burr formation [47] and the geometric features with burr width and height detected during the simulation and experimental procedure in drilling process used for the characterization of burr [47,92]. Burrs are normally formed in the uniform, transient, and crown shapes which depends on workpiece material properties, drilling parameters, cutting forces, and chips formation [93]. The uniform burrs are formed by the first fracture in the centre of the hole when the compression stress is applied by the chisel edge to the material. With the advancement of the tool, a second break occurs around the hole as the region of the plastic deformation extends from the centre of the hole to the edges of the drill. In the transient burr, the fracture occurs at the same time in the centre of the hole and around the hole at the exit. Crown burrs are large sizes around the exit hole and irregular in shape. It is worth noting that the high plastic deformation in the centre of the hole occurs due to the rise in thrust force as a result of high feed rate [47].

Other characteristics of hole quality include circularity error (roundness error) or hole size. The tolerance for rivets and bolts required in the aerospace industry while using a standard twist drill is as low as  $\pm 0.025$  mm [94]. Deviation from

the nominal size of holes i.e. diametric deviation or circularity is significant for the performance of any machined parts; however, they need more attention like surface roughness. Therefore, tight tolerances of holes are very important for achieving quality holes [95]. Table 5 shows the effect of drilling parameters on several hole quality metrics when drilling aluminium alloys.

For instance, Hassan et al. [52] recommended high speed and feed rate to reduce the burr height in aluminium. They investigated that the hole surface roughness increased at low point angle of  $110^\circ$  compared to  $130^\circ$  and when drilling at a lower feed rate. In another study by Uddin et al. [96], a smaller feed rate was recommended for dimensional accuracy of holes while no noticeable impact of the spindle speed was found. In addition, more burrs were formed when an increase in both the spindle speed and feed rate was noted. Particularly, burr size increased with the feed rate when the spindle speed was larger. In general, the burr thickness was influenced more than the burr height by the spindle speed. In case of the surface roughness, the higher spindle speed contributed more in lowering the surface roughness. Zhu et al. [24], noted that a higher feed rate increased the chip thickness which deteriorated the surface roughness, irrespective of the drill geometry and material type. It was also observed that burr height on the entry side was more visible than that on the exit side. The entrance burrs were formed from tearing, followed by clean shearing, whereas the exit burrs were formed due to the thermal effect and the plastic deformation of materials. Kumar et al. [98] explained that low cutting speed resulted in lower surface roughness, mainly due to a smaller amount of BUE. Additionally, Rimpault et al. [97] concluded that burr height was reduced with high cutting speed or low feed rate.

In regards to aspects of tool materials and coatings, the literature indicates contradicting findings. Roy et al. [99] reported that aluminium alloys have a higher chemical affinity for materials like  $TiB_2$ ,  $TiC$ ,  $Al_2O_3$ ,  $TiN$ , and  $AlON$ . Therefore, tools with a coating of these materials accumulate on the tool's surface causing a BUE due to constant release of particles during dry machining which generates high cutting forces and affects the surface quality of the workpiece. In another study by Kalidas et al. [100], three different types of coatings including multi-layer coatings i.e.  $TiAlN/TiN$ ,  $TiAlN$  and  $MoS_2$  were used in dry and wet drilling conditions. They concluded that coated tools did not show any major impact on surface roughness and temperatures in the workpiece. However, Nouari et al. [69], have concluded that carbide hardlube:  $TiAlN + WC/C$  coated drills gave low values of surface roughness. They justified this by noting that coated drills provided a thermal barrier from high temperature by restricting the diffusion process. Diffusion is a dominant process of tool wear at high cutting speeds that participates in the formation of adhesive layers at the tool-chip interface and ultimately, results in tool damage. However, based on performance, it was recommended that coated drills could be used at high cutting speeds. In another study by Kurt et al. [70], results obtained in terms of surface roughness were found to be similar after using  $TiAlN$  and  $TiN$  coated drills in dry drilling of  $Al2024$ , regardless of the point angle. Furthermore,  $Co\ 5\%$  coated drills with a point angle of  $130^\circ$  were suggested to outperform at every cutting parameter selected in their investigations. The authors did not

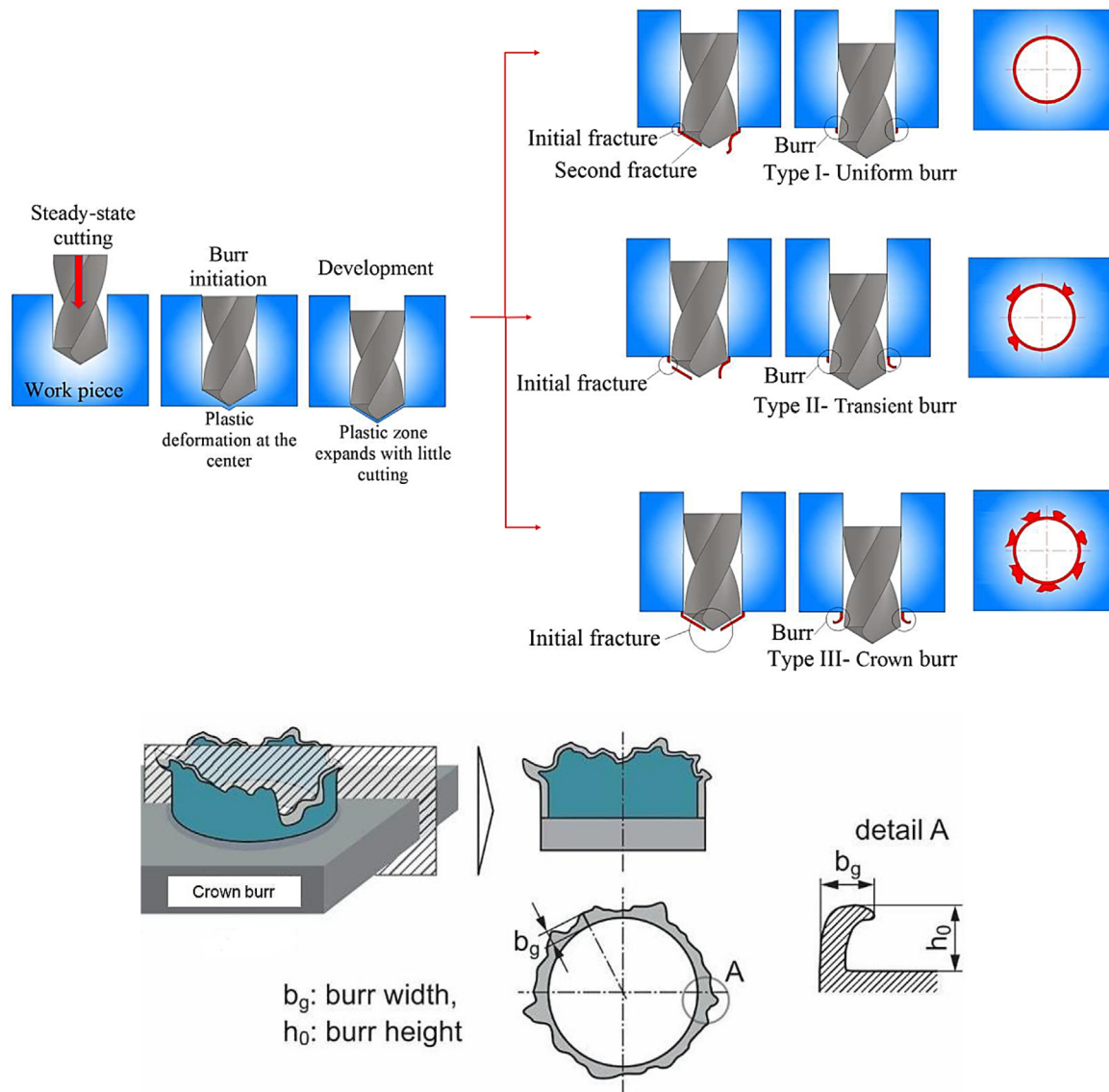


Fig. 9 – Mechanism of burr formation in a drilling process and geometric features of crown burrs [47,92].

Table 5 – Influence of input parameters on the output parameters.

Input parameters	Output parameters					
	Surface roughness		Burr		Hole size and roundness or circularity error	
	Increase	Decrease	Increase	Decrease	Increase	Decrease
↑ Speed	[53,70–73,75]	[58,96]	[72,73,78,96]	[24,52,97]	[53,70,71,74,75]	–
↑ Feed	[24,53,58,70–73,75]	[52]	[72,73,96,97]	[52]	[53,70,71,75]	[53]
↑ Point angle	[75]	[52,58,72]	[78]	[52,58,72]	[75]	–
↑ Helix angle	[52]	[58]	–	–	–	[58]
↑ Drill diameter	[73]	–	[73]	–	–	–

provide any reason based on the performance of coated drills; however, they explained other influential factors such as cutting speed and feed rate that affected the surface roughness, hole size and roundness error. They concluded that high cutting speed caused the excessive tool rubbing on the walls of the hole which resulted in the heating of the tool and consequently, the ductility of the materials increased. This in

return caused deformation of the hole and resulted in higher surface roughness. The high spindle speeds were speculated to increasing vibration and chatter which also contributed to worsening the quality of holes. It should be noted that chatter is a resonant vibration in the machine or workpiece also called the machining vibrations are caused due to relative movement between the workpiece and the cutting tool. In addition,

roundness error at the entrance of the hole was more than at the exit. The roundness error increased at high feed rate due to the generation of high cutting forces. Moreover, the point angle was found a significant factor only for evaluation of the radial deviations.

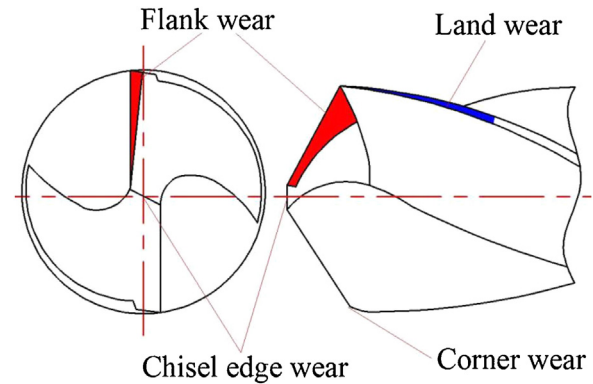
The surface roughness of aluminium alloys in machining is also affected by mechanical properties [101]. Alloys of aluminium with high ductility have more tendency to form BUE, which increases tool wear and ultimately affects hole quality especially, surface roughness and burrs [73]. However, aluminium alloys with some embedded hard particles e.g., proportions of 20% vol. SiCp [102] and 15% vol. SiC [103] can cause random pull out of the hard particles, which either stick to the tool surface causing a BUE or scratch the machine surface [102].

The above study indicates that high-quality holes require a low cutting speed and feed rate. Most of the researchers recommend HSS and carbide tools for drilling aluminium alloys. However, it has been shown that carbide outperformed than HSS. In addition, a higher point angle and helix angle was recommended for better hole quality. The advancement in drilling technologies and applications of different techniques has increased the number of studies for improving hole quality; however, there is need to further investigate the impact of different drilling parameters, tool geometries as well as tool materials and coatings.

#### 2.4. Chip formation

According to the geometrical characteristics, the chips formed in metal cutting include the continuous chips, discontinuous chips, lamellar and segmented chips. Continuous chips are formed due to high cutting speeds, low feed rates, materials with high ductility, and the tool with sharp edges [104]. Continuous chips adhere to the tool and cause a BUE whereas discontinuous chips are produced when hard or brittle materials are machined or when machining ductile materials with low feed rates and small rake angles. Discontinuous chips are desirable when hard materials are to be machined as they give a good surface finish [63]. Furthermore, lamellar chips are semi-continuous chips produced at high cutting speed and feed rate, whereas segmented chips which are a form of discontinuous chips are formed at low cutting speeds [104].

In orthogonal cutting, especially in turning and milling operation, the formation of chips is avoided as they instantly leave the cutting edge. However, the way chips formed during the drilling process can be troublesome because chips continue to flow out along the spiral flute after leaving the cutting edge. Thick chips are difficult to break by the action of the drilling process whereas continuous chips tend to entangle in the holes and affect the surface finish [105]. Furthermore, in drilling, chips can reduce productivity due to breakage of the drills as a result of clogging of their grooves because of increases in torque, which can lead to tool failure. Therefore, chip control in the drilling of aluminium alloys is important as it may have an impact on thrust force, torque, surface roughness and tool wear. Effective measures to control the formation of chips include mechanical properties of workpiece, tool geometry, cutting conditions, tool materials and coatings



**Fig. 10 – Schematic drawing of different forms of tool wear in drilling [47].**

[9]. A high Si content aluminium alloy such as 12% wt. Si also contributes to the formation of short, fragmented chips [106].

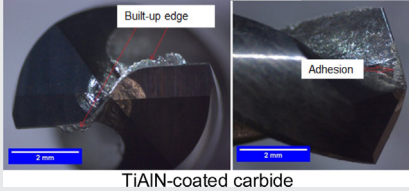
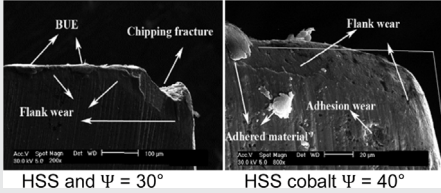
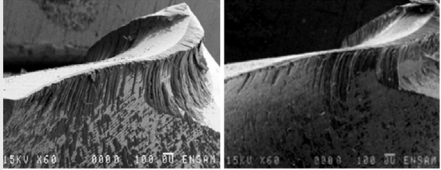
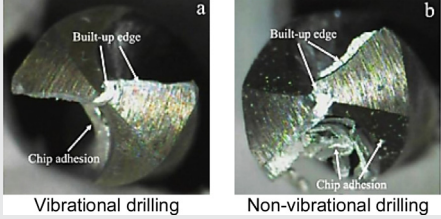
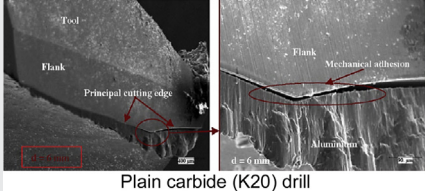
#### 2.5. Tool wear

Analysis of tool wear is important for increasing the productivity which in turns is significant for the final cost. The selection of the right tool material means a longer tool life which depends on the tool wear mechanism [33]. This is because, during tool wear, the material gradually removes from the tool and the original shape of the tool changes thus affecting the surface quality. Tool wear occurs as a result of rubbing action of metal-to-metal i.e. the tool and the workpiece that results in high temperature and generation of stresses [66]. Different tool wear mechanism includes flank wear which results from the adhesive and abrasive wear mechanism [99,102]. Other wear mechanisms include the crater wear which occurs due to abrasive wear and dissolution wear. During crater wear, the tool material dissolves into the workpiece and deteriorates the cutting edge leading to chipping [107]. Furthermore, the abrasive wear is caused either by the presence of hard particles in the workpiece or removing small portions of the tool itself [9]. Abrasive wear is mainly caused by both flank wear and crater wear; however, occurs significantly due to flank wear [63]. In addition, adhesion on the tool occurs during machining of soft materials when chips stick to the tool surface and continue to grow in size thereby causing BUE [108]. Moreover, high cutting speed during machining of aluminium increases the temperature which is sufficient to initiate the diffusion process [69]. Diffusion occurs when the atoms in the highly concentrated region transfer to a low concentrated region and depend on the temperature at the interface of tool-chip and tool-workpiece [109]. Another mechanism that contributes to tool wear is plastic deformation and chemical reactions of the cutting edge [63]. Some of the drilling tool wear mechanism is given in Fig. 10.

According to Kelly and Cotterell [110], the tool faced the greatest problem in the machining of those aluminium alloys that possess high contents of hard particles. In a study by Narahari et al. [111], it was discussed that the performance of a tool was affected by the amount of SiCp and rapid flank wear was observed even with the use of PCD tools. Coelho et al. [112]



**Table 6 – Wear mechanism in aluminium.**

Material/Drilling conditions	Wear mechanism	Ref
Al2024, D = 6, $\theta = 140^\circ$ , $\psi = 30^\circ$ n = 1000, 3000, 6000, and 9000 $V_f = 100, 300, 600$ , and 900	 TiAlN-coated carbide	Adhesion, Built-up edge [53]
Al2024, n = 1500, 5000 $f = 0.04$ $\theta = 130^\circ$	 HSS and $\psi = 30^\circ$ HSS cobalt $\psi = 40^\circ$	Adhesion, built-up edge, flank wear [74]
Al2024 D = 6 $\theta = 130^\circ$ $\psi = 30^\circ$ $V_c = 25, 65$ and 165 $f = 0.04$	 Carbide uncoated Carbide (TiAlN + WC/C)	Adhesion, built-up edge [69]
Al2024-T6 D = 5 $\theta = 118^\circ$ n = 460, 750, 1255 $f = 0.104, 0.208, 0.348$	 Vibrational drilling Non-vibrational drilling	Adhesion, built-up edge [115]
Al2024, D = 4, 6 and 8 $\theta = 118^\circ$ n = 1050, 2020 and 2750 $f = 0.05, 0.1$ and 0.15	 Plain carbide (K20) drill	Adhesion, built-up edge [116]

Symbols: Drill diameter: D (mm), Point angle:  $\phi$ , Helix angle:  $\psi$ , Spindle speed: n (rev/m), Feed: f (mm/rev), Cutting speed:  $V_c$  (m/min), Feed speed:  $V_f$  (mm/min).

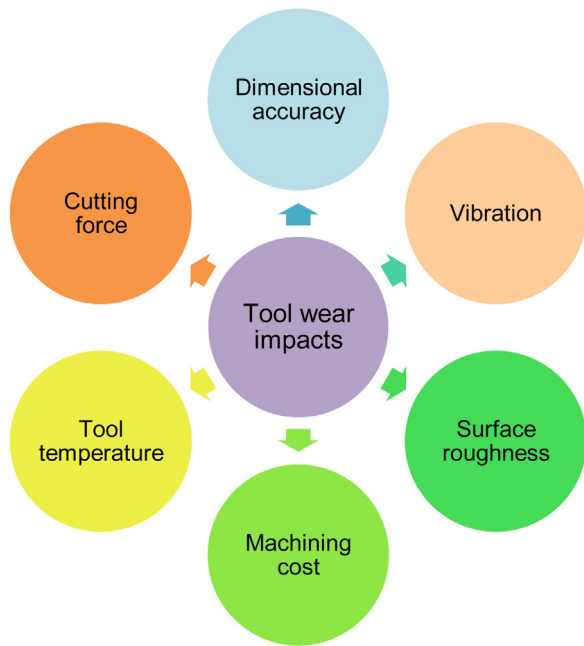


Fig. 11 – Tool wear impacts [119].

also found flank wear during drilling in alloys of aluminium with Si and SiC particles using PCD tools. Furthermore, Biermann and Heilmann [113] reported that high levels of flank wear depend on Si contents and hard particles such as  $\text{Al}_2\text{O}_3$ , SiC. On the other hand, aluminium alloys with soft matrices that have Si contents normally below 7.5% wt. Si produce less wear due to their soft and ductile nature [9]. Therefore, these alloys with no major hard particles and produce less abrasive wear; however, due to their ductile nature, there is more chance of diffusion wear and adhesion [58] where the adhesion is considered as a significant problem in machining these aluminium alloys [114]. The different wear mechanism in aluminium alloys observed in previous studies is given in Table 6.

Krishnaraj et al. [117] reported that adhesions, BUE, and diffusion on the tool are the most common problems in the drilling aluminium alloys. Therefore, the dominant wear mechanism in aluminium alloys requires better understanding to reduce tool wear which helps in increasing productivity. The significant factors affecting tool wear include drilling parameters. According to Giasin et al. [53], adhesion and BUE on the cutting edges of drills were observed due to high cutting speed and feed rate. This is because the high friction between the tool and chip from the workpiece caused the chips to weld on several regions of the cutting tool. Davoudinejad et al. [74] also observed abrasive and adhesion wear of the tools at high cutting speeds. Furthermore, during the dry drilling of Al2024, adhesion and BUE were also examined at high cutting speed by Nouari et al. [69]. The high cutting speed increased the temperature that activated the diffusion process by the transfer of aluminium from the workpiece to the tool. In addition, the coated carbide ( $\text{TiAlN} + \text{WC/C}$ ) drills were recommended for dry drilling of Al2024 at high speeds unless the cost of the tool is not

important. The adhesion and BUE in the drilling of Al2024 were also observed by Amini et al. [115] due to the long and continuous chips. They recommended a vibration drilling process for reducing the adherence of chips. In another study by Zitoune et al. [116], the high cutting speed was recommended for less BUE. Other reasons include the lower point angle which had an undesirable impact on the drill wearing [118]. Furthermore, the high drill diameter generates larger chips due to the large cross-sectional area of the chip where more chances of tool wear occur [116]. Fig. 11 shows the tool wear impacts.

### 3. Conclusions

The major problem with the drilling aluminium occurs in alloys containing high Si contents normally above 7.5% wt. and hard particles such as SiCp or  $\text{Al}_2\text{O}_3$ , include the flank wear, crater wear and abrasion wear which affect the tool life and hole quality. Alloys from 2000 and 7000 series are mainly used in the aircraft structures. Al2024-T3 is mostly used in the fuselage skin and lower wings of the aircraft where the fracture toughness i.e. resistance to crack growth is an important design parameter, while Al7075-T6 is a better choice for the upper wing skins, where the strength is the primary design factor. The major problem with these alloys is the adhesion, built-up edge and sometimes diffusion may occur, which is usually a consequence of their soft matrices. These problems along with the control of chips formation could be better solved with the used of carbide drills instead of HSS drills. The coatings do not contribute well in the drilling of aluminium; however, they are the better choice at high cutting speeds which increases productivity. The correct choice is the diamond-coated tool, but they are expensive. Regarding drilling parameters, high cutting speed and low feed rate are required to generate low thrust force and produce low torque. Furthermore, most of the studies for better hole quality including low surface roughness, fewer burrs and less deviation from a nominal size or minimum circularity error recommended a low cutting speed, a low feed rate, a higher point angle in the range of  $130^\circ$ – $140^\circ$ , a helix angle of  $30^\circ$  and a low drill diameter with the common range usually between 5 and 10 mm in aerospace alloys for creating rivets and holes. However, the effect of cutting speed and feed rate was found more on these output parameters following the point angle and drill size.

### Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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